(Coherent) (Magnetic) Resonant Soft X-ray Scattering

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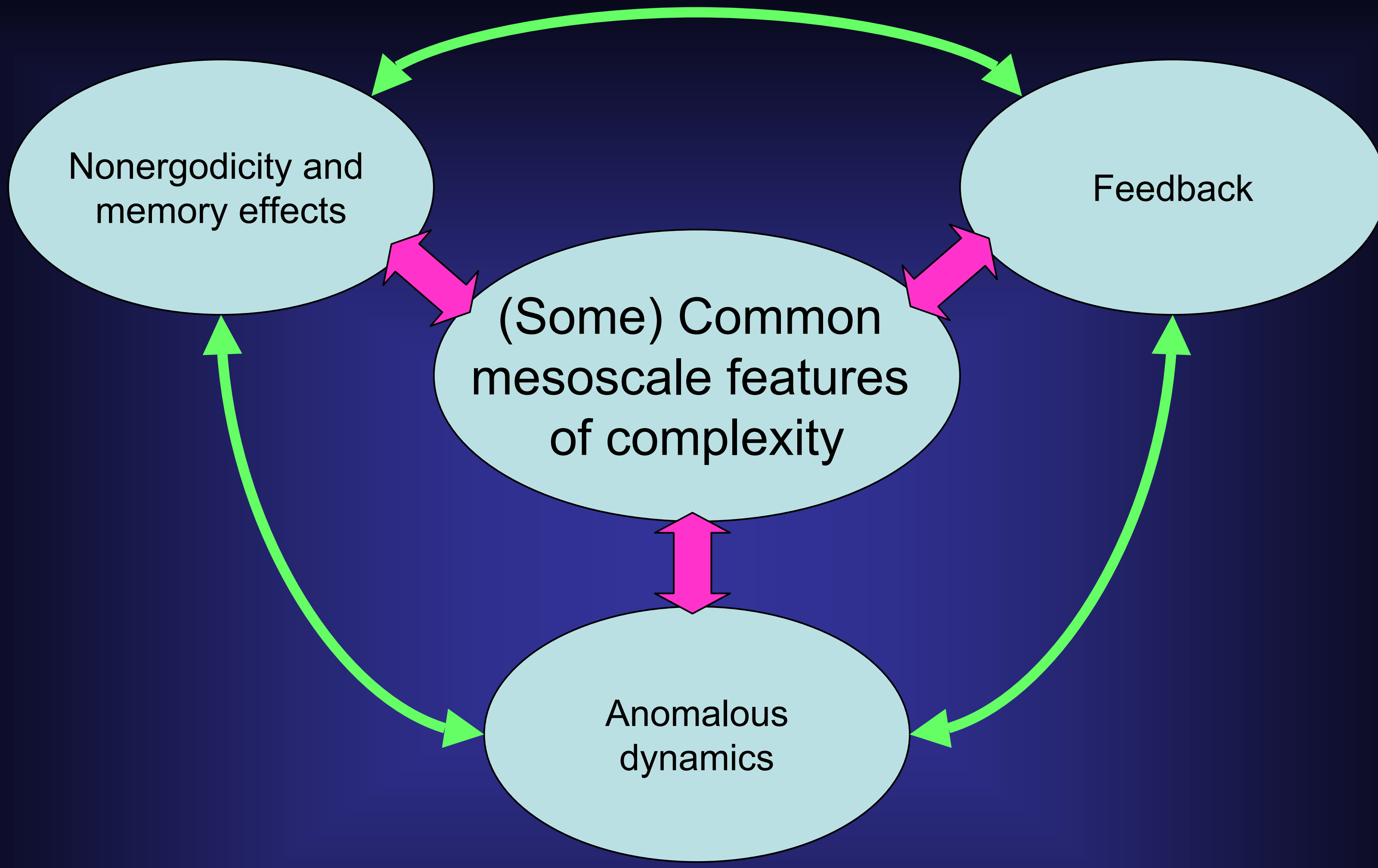
What science do we want to do?

What kind of beamline and end station do we need?

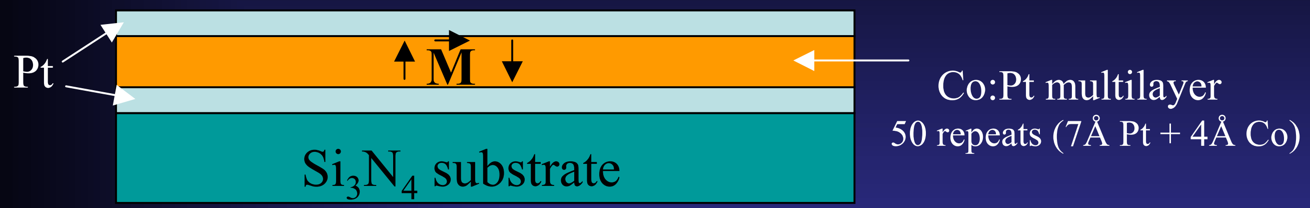
In which fund-raising effort do we belong?

Karine Chesnel	ALS/LBNL
Mark Pfeifer	ALS/LBNL
Josh Turner	Univ. of Oregon
Larry Sorensen	Univ. of Washington
Michael Pierce	Univ. of Washington
Conner Beuchler	Univ. of Washington
Jeff Kortright	LBNL
Eric Fullerton	IBM/Hitachi
Olav Hellwig	IBM/Hitachi – BESSY - Hitachi

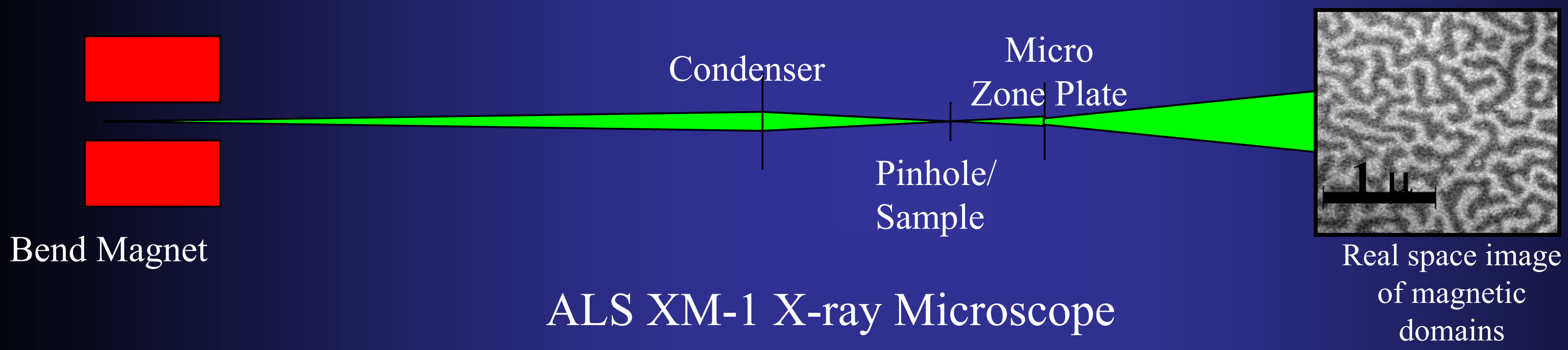


See ‘The Middle Way’, R. B. Laughlin, D. Pines, J. Schmalian, B. P. Stojkovic´i, and P. Wolynes, PNAS 97, 32 (2000).

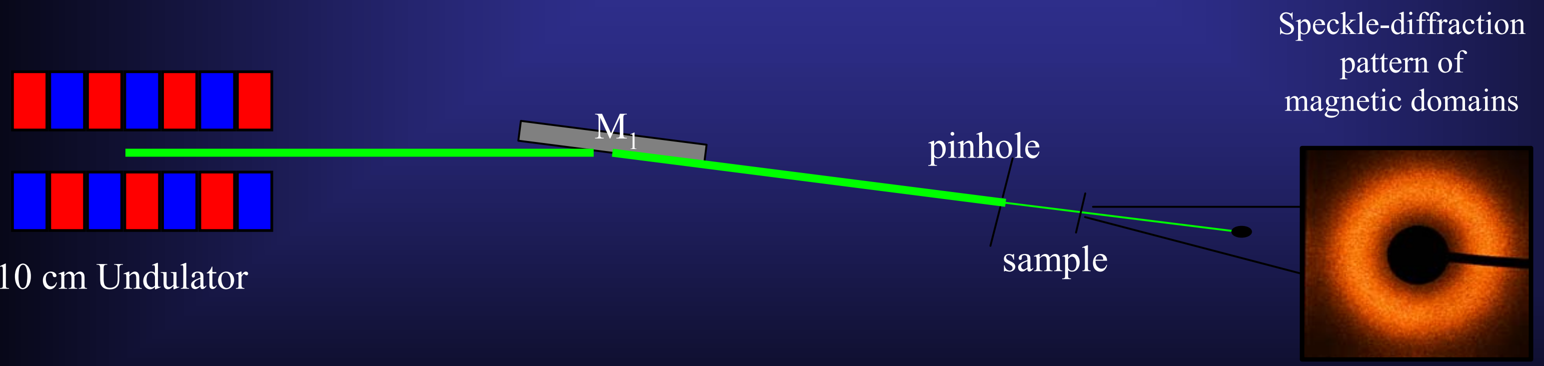
Magnetic Domains in Real and k-space using Soft X-ray Microscopy and Scattering



Magnetic contrast attained by operating near the Co L-edge

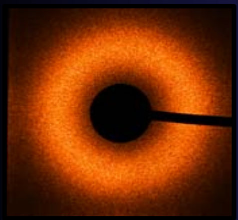


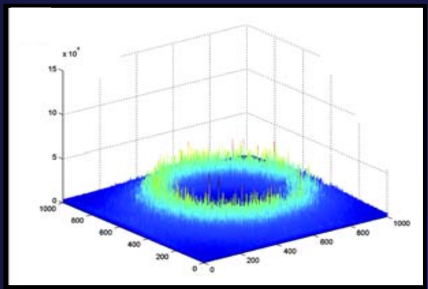
ALS XM-1 X-ray Microscope



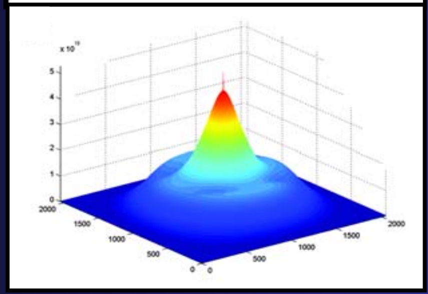
ALS BL7.0.1 (past) – BL9.0.1 ‘Blowtorch’ (recent) – BL12.0.2 CSX Beamline (current)

Soft X-ray 'Speckle Metrology' of Thin Film Ferromagnets: *a statistical measure of the similarity of magnetic domains*

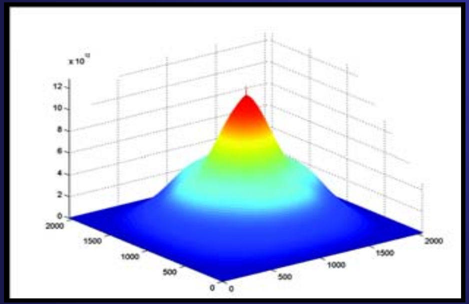




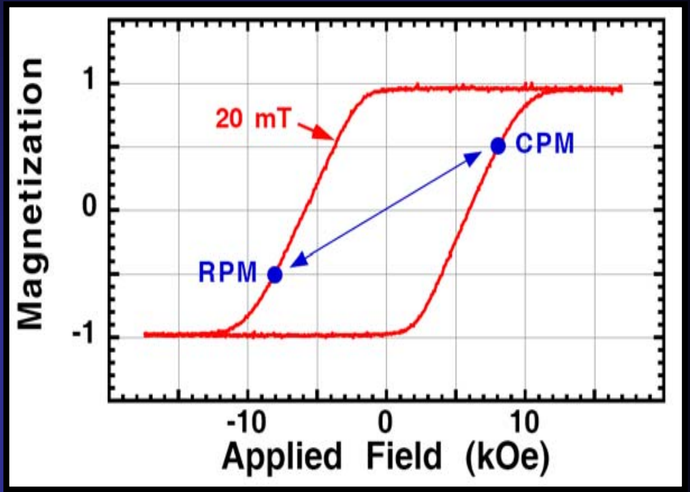
speckle pattern

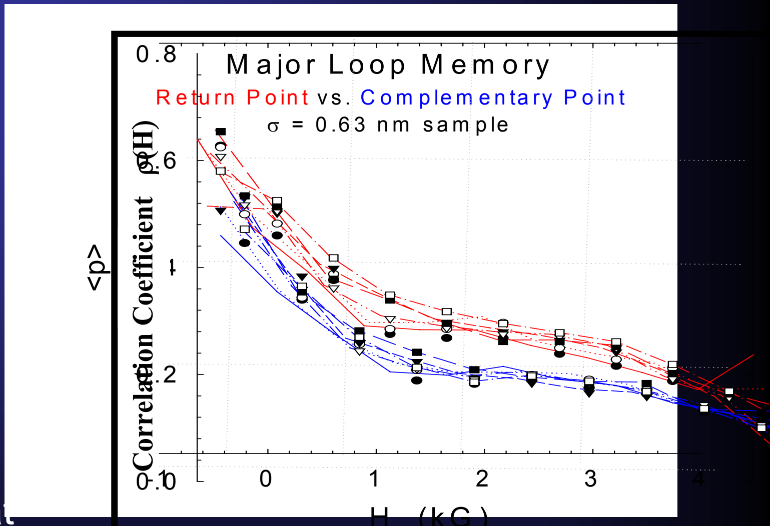


autocorrelation function



cross-correlation function



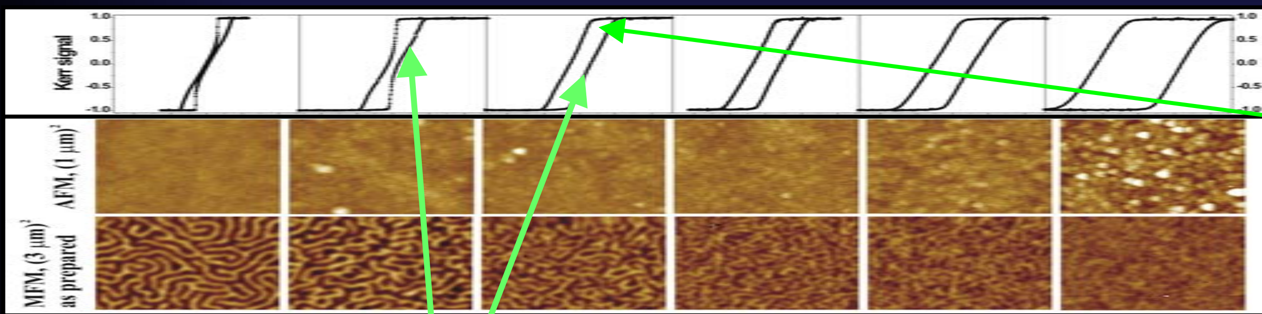


M.S. Pierce, *et. al.*, PRL, **90** 175502 (2003); PRL **94**, 017202 (2005).

The 'correlation coefficient' is essentially the integral of the speckle peak in the cross-correlation function divided by that in the autocorrelation functions.

$\rho(H) = 1$: perfect memory; $\rho(H) = 0$: perfect forgetfulness

Major Loop Microscopic Return Point Memory and Multilayer Structural Roughness



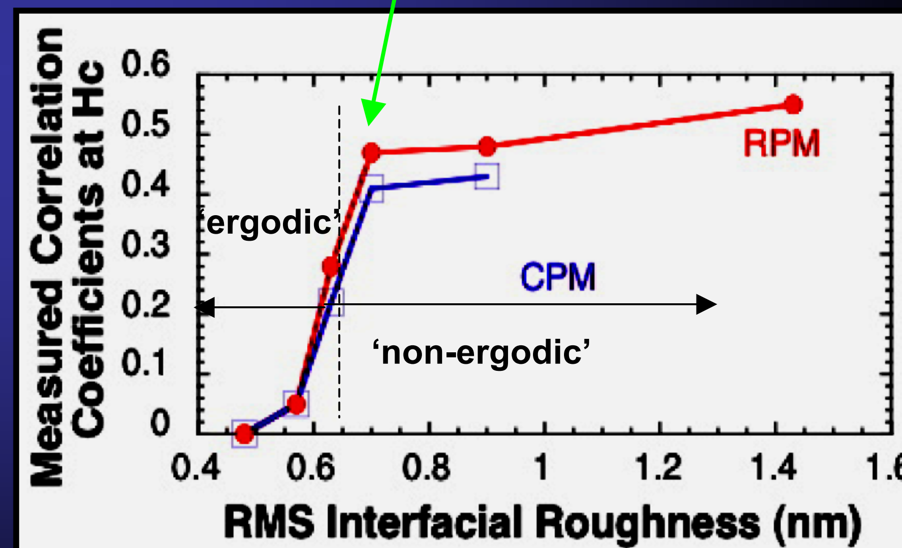
σ = 0.48 nm 0.57 nm 0.63 nm 0.70 nm 0.90 nm 1.43 nm

Roughness where a nucleation event disappears from the magnetization loop corresponds to an abrupt onset of RPM.

Theory of ‘crackling noise’ by Sethna* predicts an abrupt transition as a function of structural heterogeneity between a smooth magnetization loop and one with a distinct nucleation event, where a single Barkhausen cascade becomes macroscopic.

Multilayer perfection plays the role of a non-thermal parameter that allows us to control ergodic or nonergodic behavior.

This T=0, random field Ising theory i) does not include dipolar interactions and thus does not predict measured loops very well, ii) predicts perfect return point memory, and iii) predicts zero complementary point memory.



* see, for example, Sethna, Dahmen, and Myers, Nature **410**, 252 (2001).

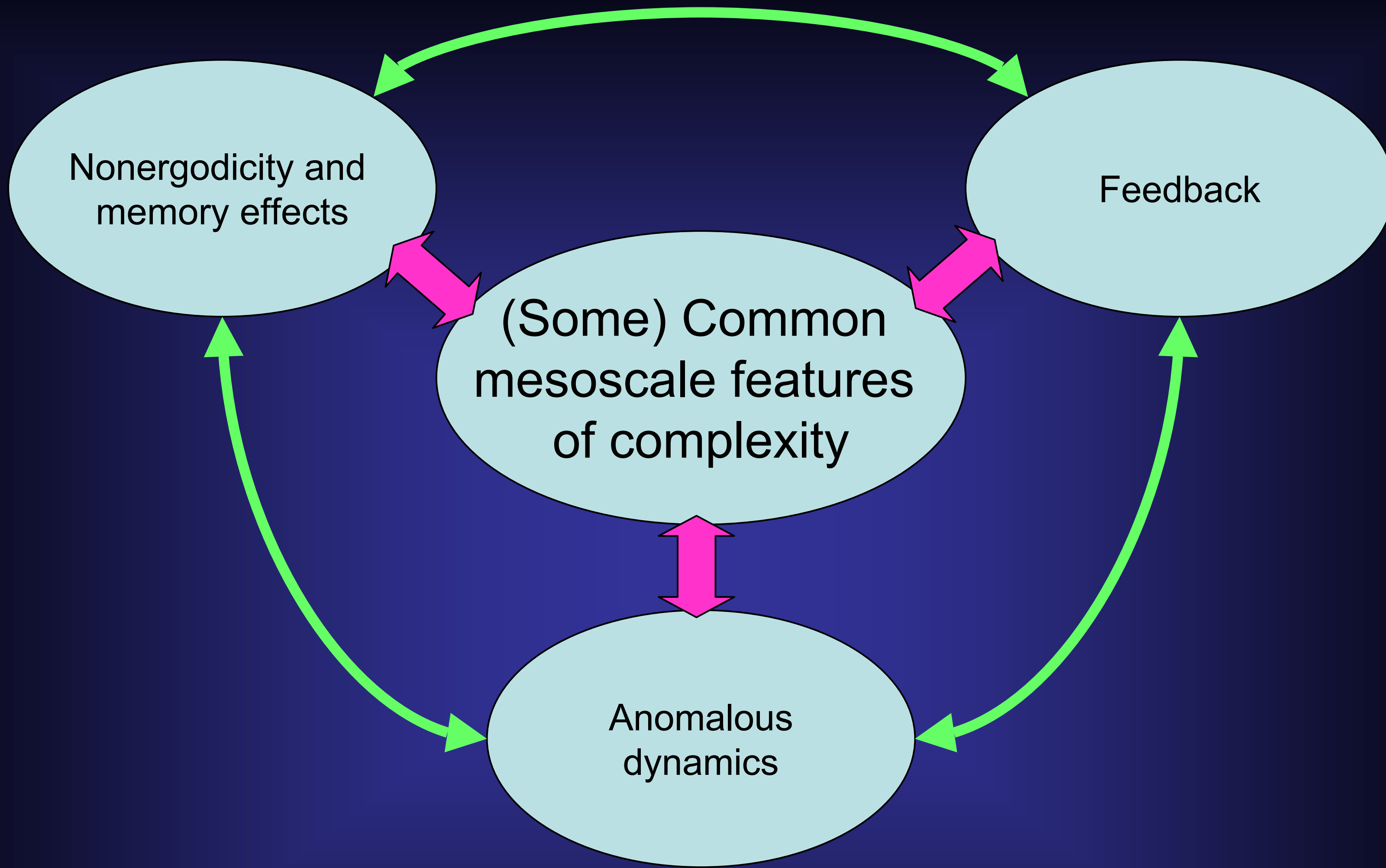
Microscopic Memory: Places to Go, Things to Do

Adding thermal and nonthermal parameters to the mix. . .

- *Exchange bias*: Proximity of an AF substrate shifts magnetization loop horizontally and (presumably) further breaks RPM/CPM symmetry. We can use the AF substrate as a controlled source of inhomogeneity.

- *Controlling the butterfly effect*: Low temperature should help the system adopt the lowest energy path and make the system less 'ergodic' (improve microscopic memory).   Can we make a scanned thermal spectroscopy of the microscopic energetics?

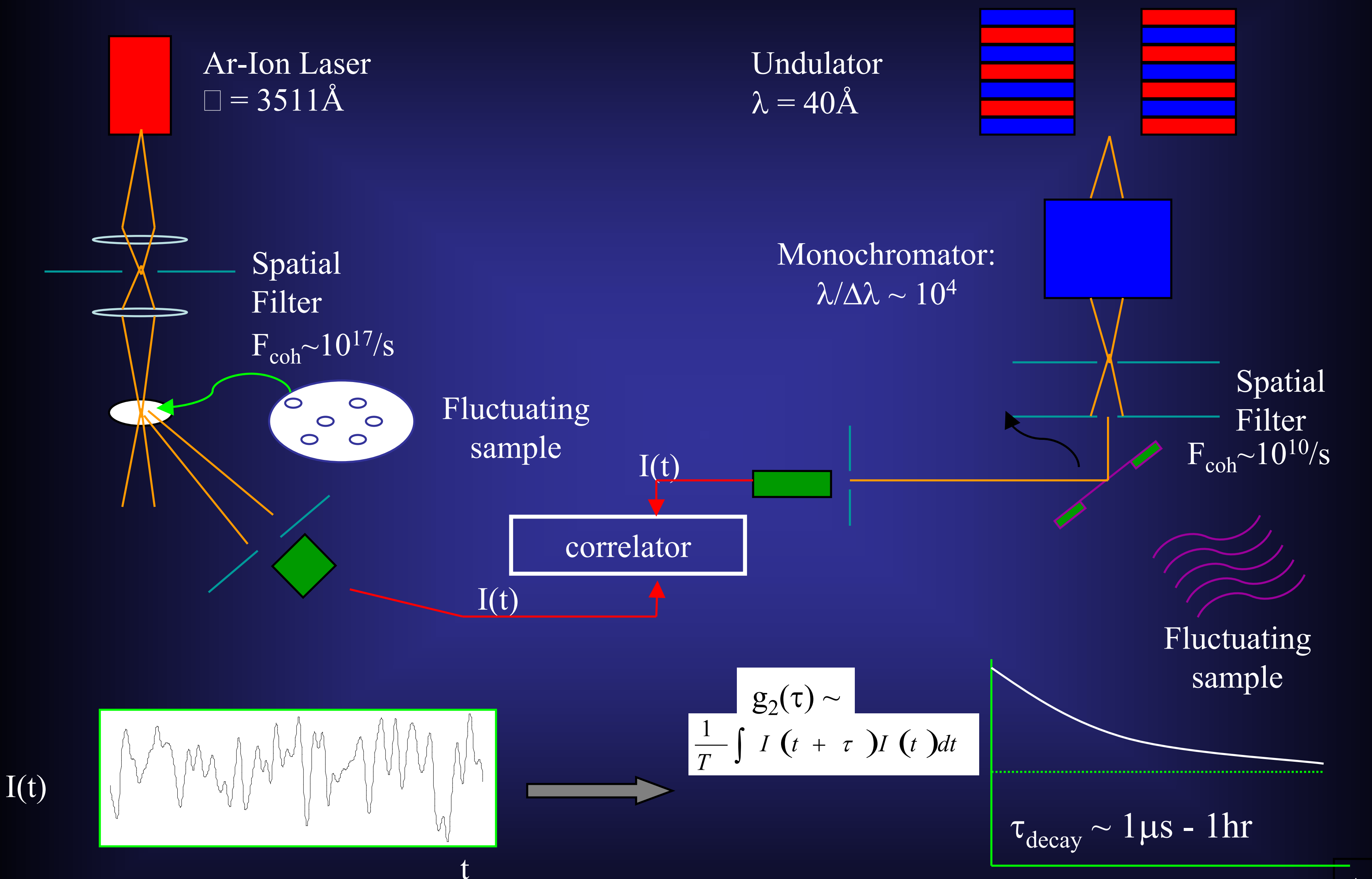
- *Other kinds of mesoscopic memory loss*: Vortex flux creep and depinning in cuprate superconductors; vortex microscopic mesoscopic memory as a function of field orientation, current density, temperature; similar issues in ferroelectrics and multiferoics (where ferromagnetic and ferroelectric distortions are coupled).



The issues are often statistical in nature and should be probed with statistical averages.

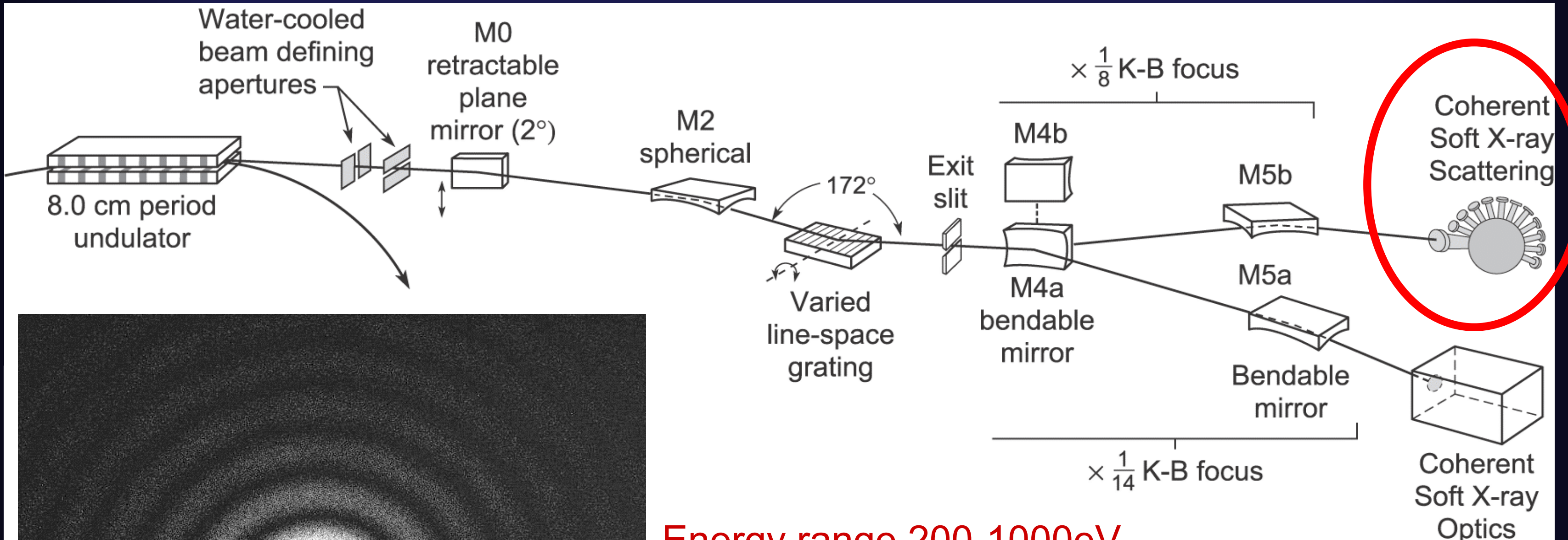
Space-time correlation functions: S(q, t, T, H, E, j, . . .)

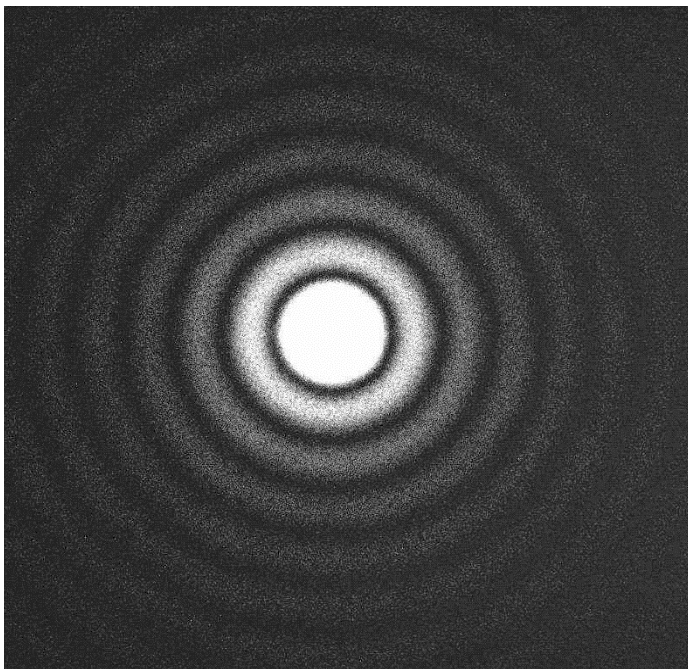
Dynamic Light Scattering



g_2(t) is the time Fourier transform of the dynamical stucture factor, S(q,ω).

ALS Coherent Soft X-ray Beamline (the current generation)





Energy range 200-1000eV

Moderate dispersion

8x demagnification of the source

Quality optics to preserve coherence

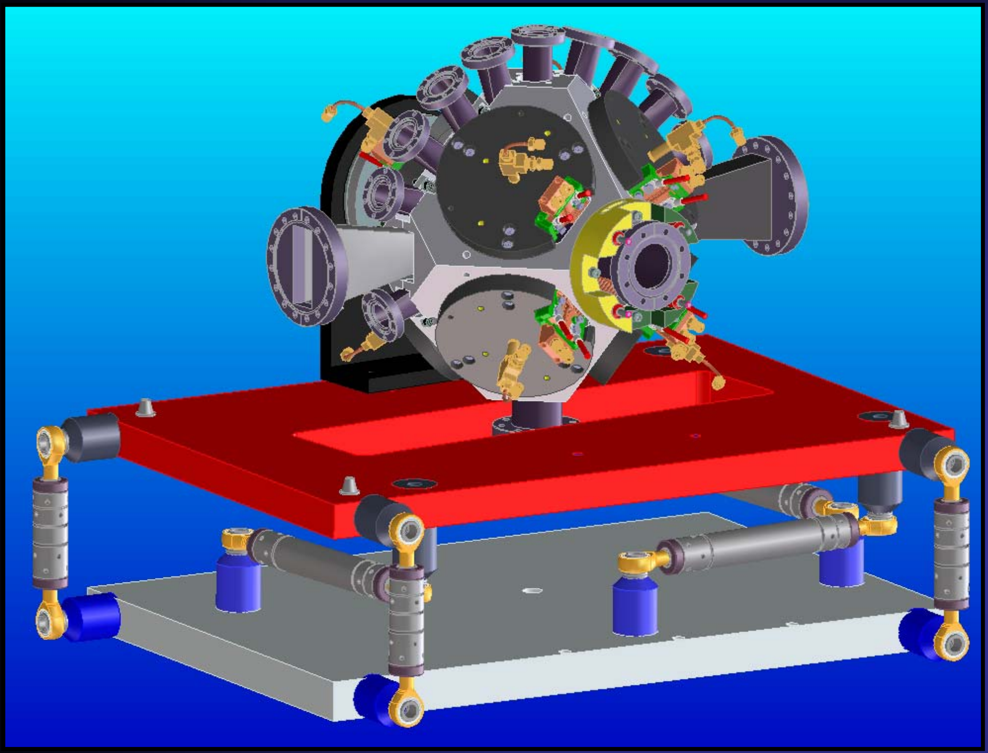
Coherent flux at 500eV: ~ 5×10^{10} ph/sec/0.1%BW

λ = 2.48 nm (500 eV)
d = 2.5 μm

Rosfjord et al. (2004)

Coh_Optics_BLwGraf.4.03.ai

‘Flangosaurus’: An End Station for Coherent Soft X-ray Magnetic Scattering



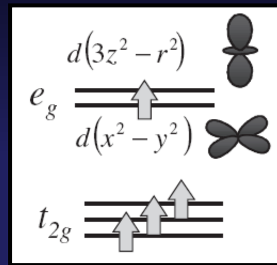
- Octapolar magnet allows fields to ~0.6T in any direction;
- Access to a full scattering plane is possible through an array of flanges coupled to chamber rotation about an axis orthogonal to the x-ray beam;
- Sample is mounted on a cryostat for T-control between ~20K and 300K;
- To help achieve the required stability, the spatial filter pinhole is mounted with piezoelectric actuation and capacitive encoding off the end of the sample stage.

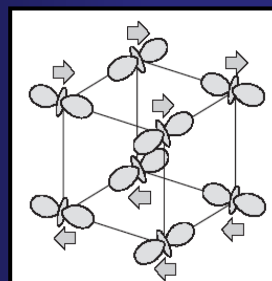
Probing Hierarchies in Space and Time

example: CMR manganites

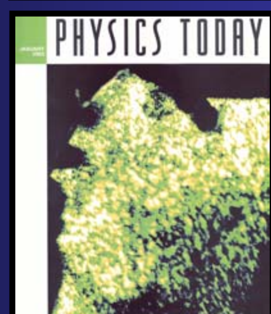
Spatial scale	Energy/time scale	Phenomenology
0.1 nm	~1 eV, 1 fsec ~1 fsec	crystal field, intra-atomic exchange and multiplets
1-2 nm	1-100 meV 100 fs – 1 ps	t-J-ology; charge, spin, orbital order; polarons, magnons, orbitons, ….
10-1000nm	< 1 neV? >1 μs?	Mesophase separation; Percolation; domain switching
Macroscopic	static/low frequency driven	CMR, etc.

Ishihara and Maekawa, Rep. Prog. Phys. **65** (2002) 561–598

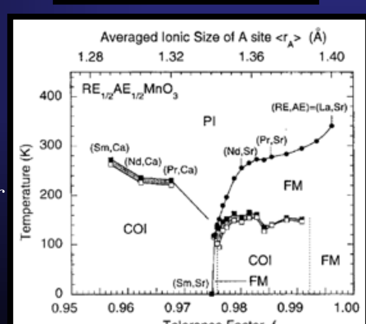




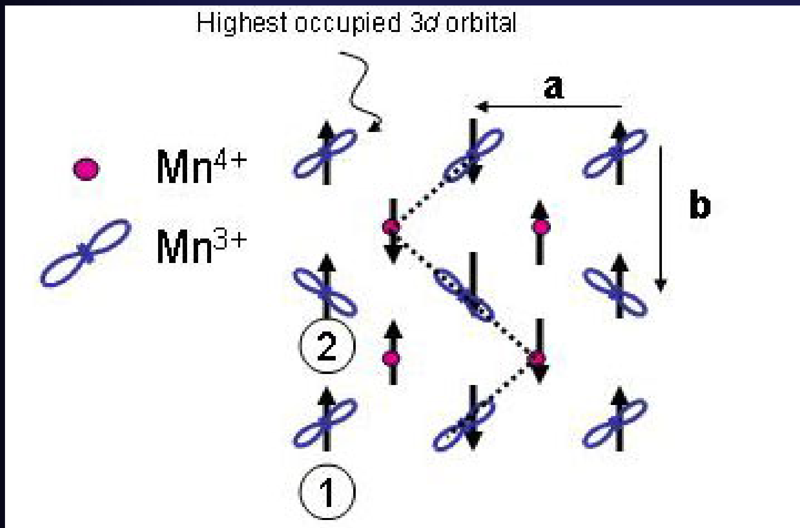
Mathur and Littlewood, Physics Today, Jan. 2003, p. 25.



Kuwahara and Tokura, in *CNR, Charge Ordering and Related Properties of Manganites*, p. 217.



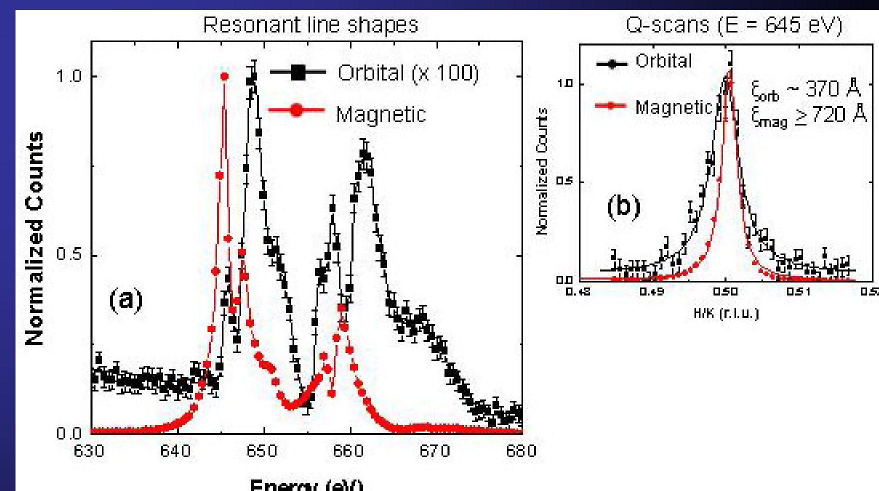
L-edge Structure in Orbital Ordered Manganites



'Conventional' picture of spin and charge ordering in $Pr_{0.6}Ca_{0.4}MnO_3$

- Mn 3d orbital physics helps determine the overall ground state;

- L-edge anomalous diffraction offers a direct probe of how the atomic interactions couple to nanoscale spin and charge structures.

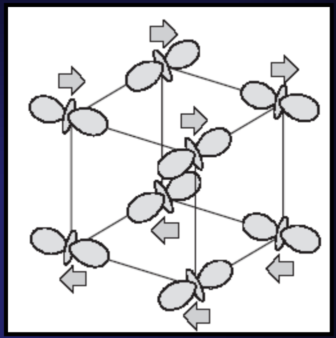


Resonant diffraction from magnetic- and charge-ordered superstructures (from X1B at the NSLS)

K.J. Thomas, J.P. Hill, S.Grenier, Y.-J. Kim, P. Abbamonte, L. Venema, A. Rusydi, Y. Tomioka, Y. Tokura, D.F. McMarrow, G. Sawatzky, and M. van Veenendaal, PRL 92, 237204 (2004).

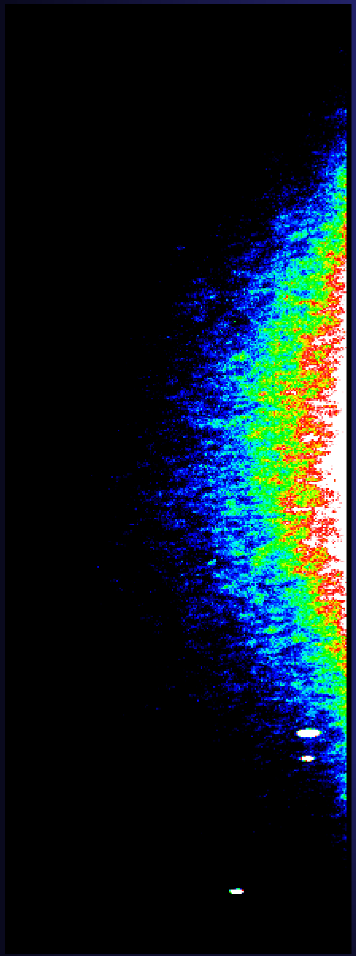
(Part of the) (1/4,1/4,0) Orbital-Order Reflection in $Pr_{1-x}Ca_xMnO_4$ Manganites

(with Jessica Thomas and John Hill, BNL)

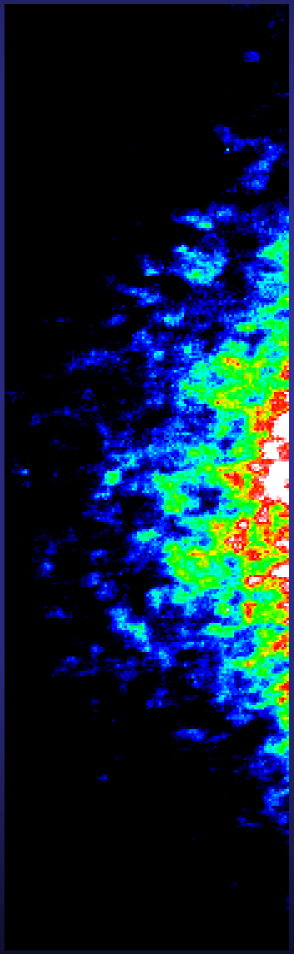


- Fluctuations of OO 'domain walls'
- Phase retrieval and imaging of OO domains
- Coupling between AF and OO domains

(but we need to get the peak in the middle of the camera. . .)



Limited coherence



Better coherence

What Do Coherent Scatterers Need?

- Energy range
  - essential: 500 eV – 1650 eV
  - advisable: 280 eV – 1650 eV
- An EPU is essential, first harmonic from ~280 eV to ~1 keV
- Demagnification/coherence length/trade signal for q-resolution
  - coherence length ~5 microns; demagnification ~ 10
  - stigmatic focus at pinhole/sample
- Band width
  - coherent illumination: $100 < E/\Delta E < 1000$
  - edge structures: $\Delta E \sim 1.0$ eV
- Other
  - pinhole and sample stability as a function of t, T, H, . . .
  - type of magnet: electro, superconducting, with or without yoke?
  - very many detector issues: speed, quantum efficiency, parallelism, dynamic range, solid angle, inside vs outside magnet, integrated logic, energy analyzer . . .

Where Do Coherent Scatterers Belong: CSX or RSXS?

- Coherent soft x-ray scattering community is small; we need more maniacs and these are likely to come from the larger resonant scattering community (that's one reason I'm here)

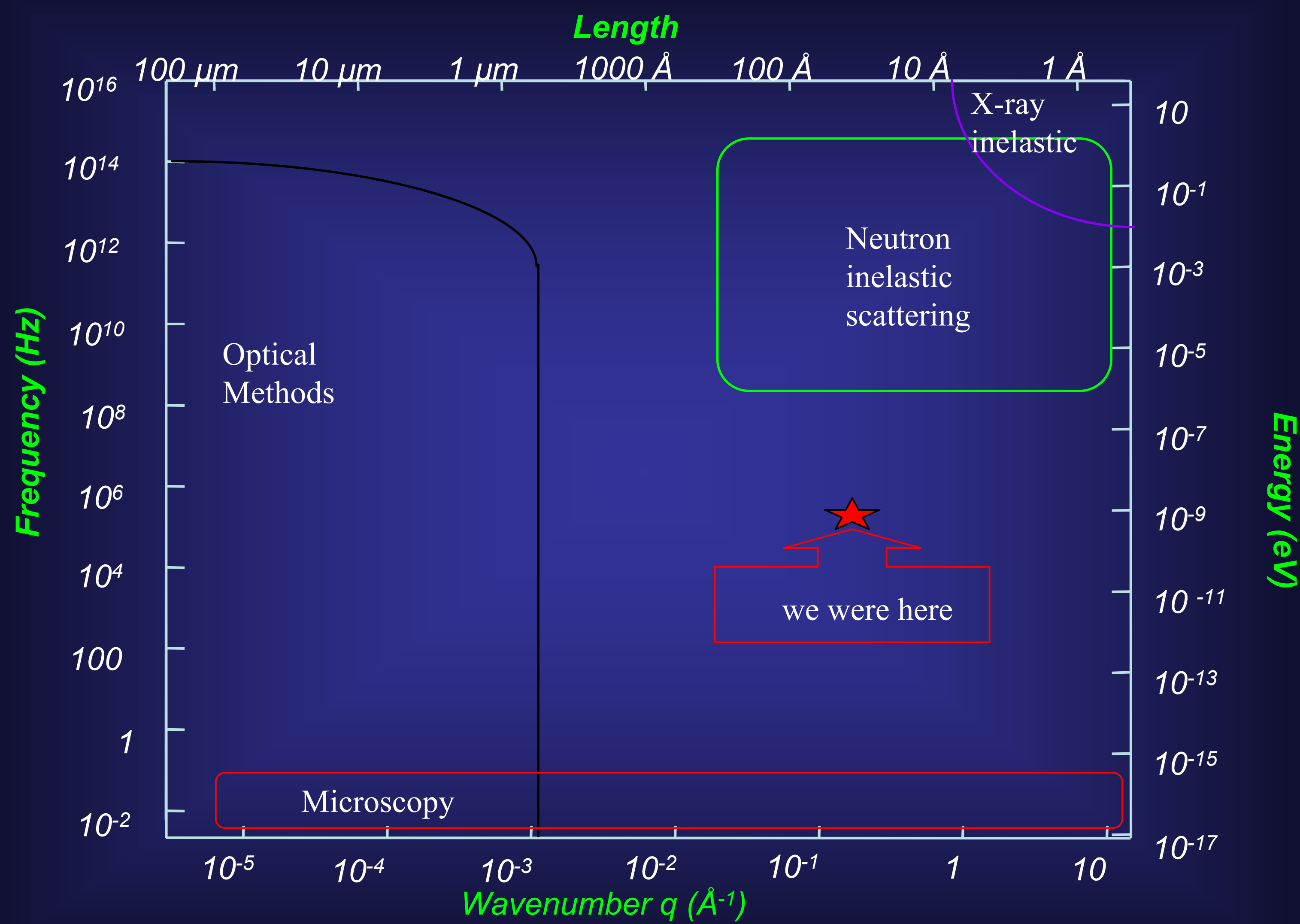
- Our instrumentation needs are similar to those of the diffractive imaging

- Our long term scientific focus is closer to that of the resonant scattering community (that's the other reason I'm here)

- CSX community is well along in the planning process with a good chance of producing a successful proposal – arguably a better chance than the RSXS community

- The current CSX beamline is in sector 12, which is where the new CSX beamlines/facility is planned. There could be a rocky transition if we jump to the RSXS project.

Probing Hierarchies in Space and Time



★ "Soft X-ray Dynamic Light Scattering from Smectic A Films", A.C. Price, L.B. Sorensen, S.D. Kevan, J.J. Toner, A. Poniewrski, and R. Holyst, Phys. Rev. Lett., **82**, 755 (1999).

Many low energy degrees of freedom: *soft&bio, sand piles*

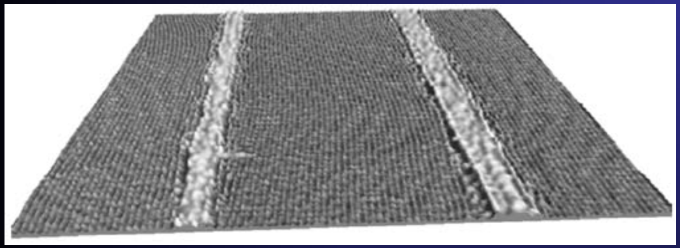
Competing high E degrees of freedom: *TMO, heavy Fermion*

Materials Complexity

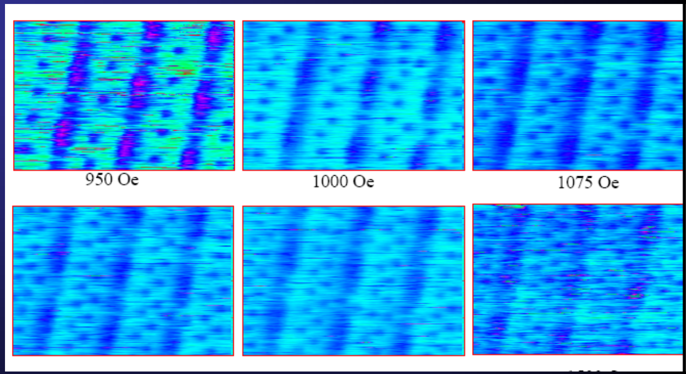
Copolymers, bioassembly

SC devices and vortices

Mesoscale and nanoscale patterning: *QHE, GMR, SQUID*



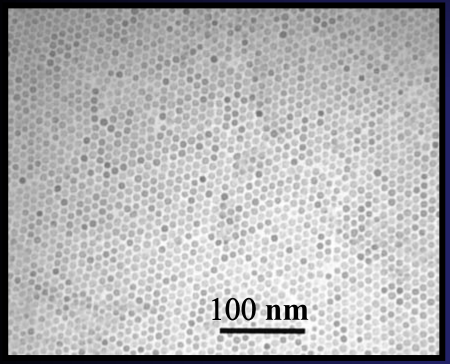
Aligned block copolymer stipes on a patterned substrate, Sibener group, U. Chicago



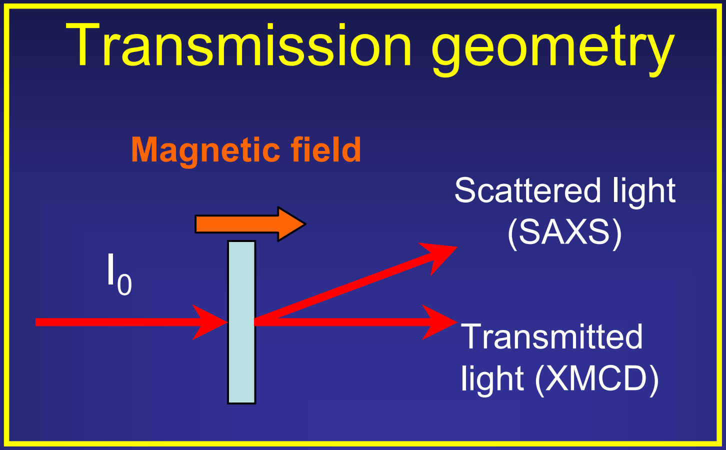
SC vortex chains and phase transitions in patterned $NbSe_2$, Goran Karapetrov, ANL

Spatial (√) and Temporal (?) Fluctuations in Co and Fe_3O_4 Nanocrystals

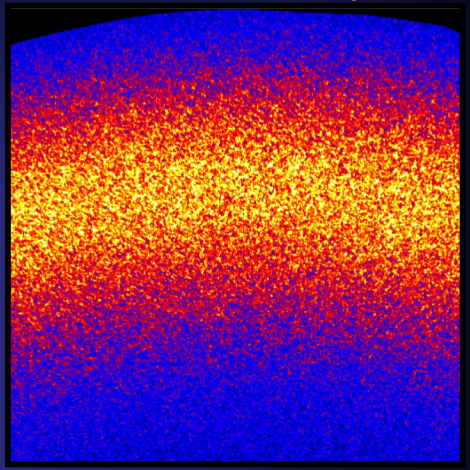
‘representative’ TEM



Puntes, Krishnan, and Alivisatos, Science 291, 2115 (2001).



Speckle pattern at the Co L_3 resonance



~10^3 photons/sec/speckle

14 nm diameter Co nanocrystals have a blocking temperature of ~200K, above which the particles are superparamagnetic:

- At low T, does the nanoparticle lattice exhibit significant microscopic return point memory?
- Can we detect superparamagnetic fluctuations?
- Can we measure the full intermediate scattering function, S(q,t), to probe the microscopic switching dynamics?

We want an EPU for Christmas (but we knew that a long time ago and it’s not going to happen that soon).